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ORIGINAL RESEARCH

Multi-criteria analysis of building assessment regarding energy performance using a life-cycle approach

Silvia Vilcekova · Eva Kridlova Burdova

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Abstract The sustainability assessment methods used over the world were the basis of new system development for Slovak conditions. The proposed fields are site selection and project planning; building construction; indoor environmental quality; energy performance; water and waste management. The evaluated indicators were proposed on the basis of available information analysis from particular fields of building environmental assessment and also on the basis of our experimental experiences. The aim of this paper is to present developed building environmental assessment system oriented to energy performance and the significance weight determination. Percentage weight of fields and indicators was determined on the basis of their significance, according to mathematical method.

Keywords Buildings · Energy performance · Environmental assessment

Introduction

Buildings are associated with large environmental impacts over a long duration. They consume an enormous amount of energy and other resources, and they contribute to carbon emissions at each stage of the building project, from design and construction through operation and finally to demolition [1, 2]. The identification of the building sector as one of the key consumers of energy led to the creation of some rules targeted at improving the energy performance of buildings down to nearly zero through the reduction of energy consumption during the occupation phase [3]. This energy consumption for a building is considered to be the energy used to maintain the occupants' comfort inside the building (energy for heating, cooling, lighting, etc.). When taking the entire building life cycle into account, total energy used includes operational and embodied energy [4]. The assessment of energy performance of buildings is very important for achieving sustainable development. The aim of the building environmental assessment tools is to provide a sustainable building design, construction, operation, maintenance and renovation, which require cooperation between civil engineers, architects, designers, environmentalists and other experts from different areas of building performance. The relatively new approach of making a sustainability assessment of buildings requires the quantification of impacts and aspects of the environmental, social and economic performance of buildings using quantitative and qualitative indicators. These indicators are included in systems and tools used in various countries for the integrated assessment of buildings. The Slovak building environmental assessment system (BEAS) involves the evaluation of the following fields: site selection and project planning, building construction, the indoor environment, energy performance, water management and waste management [5]. Life-cycle assessment (LCA) belongs to a broadly used methodology which helps with decision-making on sustainable building design. The significance of LCA lies in the fact that it equips policy makers and decision makers for the adoption of suitable and sustainable energy supply systems. Increasing global concern about air pollution and limited oil reserves has generated a great deal of interest in environmentally friendly

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S. Vilcekova (✉) · E. Kridlova Burdova
Institute of Environmental Engineering, Faculty of Civil Engineering, Technical University of Kosice, Vysokoskolska 4, 042 00 Kosice, Slovak Republic
e-mail: silvia.vilcekova@tuke.sk

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alternatives [6, 7]. Many works studied problems of life-cycle assessment of concrete through a variety of environmental indicators [8, 9]. The goals of energy performance are: to reduce total building energy consumption and peak electrical demand; to reduce air pollution, contributions to global warming and ozone depletion caused by energy production; to slow down the depletion of fossil fuel reserves; and to lower energy costs and gain related savings due to upgrades to infrastructure. Energy consumption in buildings takes place in two different ways: energy capital that goes into the production and transportation of building materials and the assembling of the building itself (embodied energy), and the energy needed to maintain the building during its useful life. This paper deals with the proposal of a building environmental assessment system, especially one dealing with the assessment and weighting of the energy performance of buildings in Slovakia.

Energy performance of buildings

Within the European Union (EU) energy use by the built environment represents more than 40 % of total energy consumption [10, 11], with attention paid to energy and the environment currently growing in the everyday political agenda, even at a local level. As pointed out in the Agenda 21 document approved at the Rio Conference in 1992, local administrations can play a fundamental role in increasing sustainability by acting according to the well-known motto "think globally, act locally"; the inspiring principles of the Local A21 process are a suitable tool for designing a strategic road map to sustainability [12]. In line with the European Union's Energy Performance of Buildings Directive (EPBD), all new buildings within the union must be nearly zero-energy by the end of 2020 [10]. To quantify the effect of energy-saving measures in the built environment, different methodologies with accompanying indicators have been, and still are being developed. Because of the European EPBD [13], many indicators have been developed to express the energy performance of European buildings through use of an energy label with a classification system with grades from A to G. Now that Energy Performance Certification is compulsory within the European Union, it might be useful to relate the value of real estate objects to the life-cycle costs of energy-saving measures [12]. Promotion of energy efficiency is one of the main goals of energy policies since it improves resource management and reduces energy use and environmental impacts. Today most developed nations include a section on energy efficiency within their energy planning policies, usually implemented through a series of laws, codes, strategies, regulations and certification schemes [14].

Table 1 shows the most significant and globally used building environmental assessment systems [15–23] and main fields related to energy assessment.

Environmental assessment system of buildings in Slovakia

In recent years, the evaluation of building performance in terms of environmental, social and economic aspects has become a topic of discussion in the Slovak Republic. A new Building Environmental Assessment System (BEAS) has been developed at the Institute of Environmental Engineering, Technical University of Košice. Systems and tools used in many other countries were the foundation of this new system developed for application in Slovak conditions. The main fields and relevant indicators of BEAS were proposed on the basis of available information from particular fields of building performance in Slovakia and also according to our own experimental experience. BEAS as a multi-criteria system includes environmental, social and cultural aspects. The proposed fields and indicators respect and adhere to Slovak standards, rules, studies and experiments. The presented system was developed for use during the design stage of office buildings. This system for Slovakia contains 6 main fields and 52 indicators. For the purpose of system weighting, the analytical hierarchy process (AHP) was used [5]. The hierarchy structure of BEAS is shown in Table 2.

The proposed main fields are: A—site selection and project planning, B—building construction, C—indoor environment, D—energy performance, E—water management, and F—waste management.

The methodology for the derivation of the assessment indicators in BEAS was elaborated according to a study [24] and the list of indicators derived through a three-step process. To establish a comprehensive set of indicators for this method of building environmental assessment for office buildings, existing methods of building environmental assessment used worldwide were combined with valid Slovak standards and codes and an academic research paper. A three-step process was carried out. In the first step, a full range of indicators relating to sustainable building efficiency were collected through an extensive review of the literature. In step two, a draft indicator list was selected from the full indicator list based on an in-depth analysis, and in step three, a survey was conducted to gather comments from experts to refine the selected draft indicators. As a result, a final indicator list was then proposed. This list is presented for the field of energy performance in the following sections of this paper.

Table 1 Energy performance field in the most significant building environmental assessment systems

System	Energy performance field	Weight (%)	Indicators
BREEAM	Energy	19	Reduction of CO_2 emissions
			Energy monitoring
			Energy efficient external lighting
			Low or zero carbon technologies
			Energy efficient cold storage
			Energy efficient transportation systems
			Energy efficient laboratory systems
			Energy efficient equipment (process)
			Drying space
Green Globes	Energy	38	Energy performance
			Reduced energy demand
			Integration of energy efficient systems
			Renewable energy sources
			Energy efficient transportation
SBTool	ENERGY and resource consumption	22.5	Total life cycle non-renewable energy
			Electrical peak demand for facility operations
			Renewable energy
			Materials
			Potable water
LEED	Energy and atmosphere	36.4	Regional materials
			Rapidly renewable materials
			Certified wood
CASBEE	Energy	20	Building thermal load
			Natural energy utilisation
			Efficiency in building service system
			Efficient operation
BEAM	Energy use	41.3	Annual energy use
			Energy efficient systems
			Energy efficient equipment
			Provisions for energy management
			Building design for energy efficiency
SABA	Energy efficiency	23.1	Building envelope performance
			Renewable energy
			Natural lighting/lighting
			Energy efficient heating/cooling system
			Mechanic systems
			Greenhouse gases emission
			Machines/appliances
Estidama	Resourceful energy	26.4	Community energy strategy
			Building guidelines
			Energy monitoring and reporting
			Community strategies for passive cooling
			Urban heat reduction
			Efficient infrastructure
			Renewable energy: onsite, offsite
			Energy efficient buildings

Significance weighting of the energy performance field

Multi-criteria decision analysis (MCDA) through mathematical methods can help clarify choices between alternative solutions based on many, often conflicting, criteria and aspects. It seeks to integrate several goals to arrive at the most suitable solution, considering along the way the relative importance of each goal, and offers the possibility of developing a deeper understanding of the problem. If necessary, a section is dedicated to the experimental part, where the teams and means used to develop the work are briefly described [25, 26].

The significance weights of the energy performance field and indicators were determined using the mathematical analytic hierarchy process (AHP), the Saaty method and the pairwise comparison method (the Fuller method). Determined weights of significance were analysed and compared with weights of significance determined in various other systems used around the world. On the basis of comparison and consistent analysis of several variants, the most suitable variant was determined by the Saaty method. In Table 3, an example of field D—energy performance weighting by Saaty—is presented. The criteria weights were determined using the Saaty matrix, a concrete example of which is in the first part of the table with rows and columns marked D1, D2, D3. Di means the ith criterion of D—energy performance weighting for $i = 1, 2, 3$. The values of the Table 2 in columns $P(i)$, $R(i)$, $v(i)$ were computed using the following Eqs. (1–3). In the last column of the table are percentage weights of assessment criteria. The weights of all assessment criteria in main field D—energy performance—were determined using the same method and all computed values are given in Tables 3, 4, 5, and 6.

Table 2 Hierarchy structure of BEAS

BEAS									
A		B		C	D			E	F
A1	A2	B1	B2	C1	D1	D2	D3	E1	F1
A1.1	A2.1	B2.1	B2.1	C2	D1.1	D2.1	D3.1	E2	F2
A1.2	A2.2	B2.2	B2.2	C4	D1.2	D2.2	D3.2	E3	F3
A1.3	A2.3	B2.3	B2.3	C5	D1.3	D2.3		E4	
A1.4	A2.4	B2.4		C6	D1.4				
A1.5	A2.5	B2.5		C7	D1.5				
A1.6	A2.6			C8					
A1.7	A2.7			C9					
A1.8				C10					
A1.9									
A1.10									

$$P(i) = \prod_{j=1}^{n} a(i,j) \quad (1)$$

$$R(i) = \sqrt[n]{P(i)} \quad (2)$$

$$v(i) = \frac{R(i)}{\sum_{i=1}^{n} R(i)} \quad (3)$$

where n is the dimension of the Saaty matrix, $a(i,j)$ the element of the Saaty matrix of ith row and jth column, $P(i)$ the product of all elements of the Saaty matrix ith row, $R(i)$ the quadratic average of the Saaty matrix ith row and $v(i)$ the weight of ith criterion

Table 3 Saaty matrix of field D—energy performance

$a(i,j)$	Criteria			$P(i,j)$	$R(i)$	$v(i)$	Weights (%)
Criteria	D1	D2	D3				
D1	1.00	5.50	2.00	11	2.224	0.692	69.2
D2	0.18	1.00	1.00	0.181818	0.567	0.176	17.6
D3	0.15	0.50	1.00	0.076923	0.425	0.132	13.2
Total					3.780	1.000	100

In Tables 4, 5, and 6, the weighting of indicators in the subfields are presented:

- D1—operation energy,
- D2—active systems using renewable energy sources and
- D3—energy management.

The criteria weights were assigned using the Saaty matrix.

Table 4 Saaty matrix of subfield D1—operation energy

$a(i,j)$	Criteria					$P(i,j)$	$R(i)$	$v(i)$	Weights (%)
Criteria	D1.1	D1.2	D1.3	D1.4	D1.5				
D1.1	1.00	2.00	3.50	5.00	5.00	175	2.809	0.438	43.8
D1.2	0.50	1.00	3.50	4.00	4.00	28	1.947	0.304	30.4
D1.3	0.29	0.29	1.00	2.00	2.00	0.163265	0.696	0.109	10.9
D1.4	0.20	0.25	0.50	1.00	1.00	0.025	0.478	0.075	7.5
D1.5	0.20	0.25	0.50	1.00	1.00	0.025	0.478	0.075	7.5
Total							5.801	1.000	100

Table 5 Saaty matrix of subfield D2—active systems using renewable energy sources

a(*i,j*)	Criteria				*P*(*i,j*)	*R*(*i*)	*v*(*i*)	Weights (%)
Criteria	D2.1	D2.2	D2.3	D2.4				
D2.1	1.00	2.00	1.00	1.00	2	1.260	0.413	53.5
D2.2	0.50	1.00	1.00	0.50	0.5	0.794	0.260	16.5
D2.3	1.00	1.00	1.00	1.00	1	1.000	0.327	22
Total						3.054	1.000	100

The significant weights of the criteria were determined using various methods presented in Table 7. The determined weights of significance were analysed and compared with weights of significance determined in various systems used around the world. On the basis of comparison and consistent analysis of four variants, the most suitable variant is that determined by the MCA—the Saaty method.

Results and discussions

According to the presented methodology for derivation of indicators for assessment and significance weighting, the percentage weights and the means of the assessment of indicators related to energy performance of buildings are presented in Table 8.

Table 6 Saaty matrix of subfield D3—energy management

a(*i,j*)	Criteria		*P*(*i,j*)	*R*(*i*)	*v*(*i*)	Weights (%)
Criteria	D3.1	D3.2				
D3.1	1.00	1.00	1	1.000	0.500	50
D3.2	1.00	1.00	1	1.000	0.500	50
Total				2.000	1.000	100

In this paper, the indicators related to the field of energy performance and method for determining the significance weight of this field in BEAS are presented. The percentage weights for energy performance field in the significant environmental assessment systems vary from 19 to 41.3 %, the lowest significant weight of 19 % for BREEAM and the highest of 41.3 % for BEAM. Energy performance in BEAS has a percentage weight of 26.45 %, which corresponds with the mean percentage weight of 28.33 % determined for selected significant systems used in the world (Table 1). The field of energy performance in BEAS consists of 3 subfields and 11 indicators. Within this field the subfield, D1—operational energy has a weight of 56.25 %, the second subfield, D2—active systems using renewable energy sources has 25 % and the third subfield, D3—energy management has 18.75 %.

Conclusions

Building environmental assessment systems and tools has been developed for various types of buildings and for each stage of their life cycle, comparison of the methods and tools developed in different countries showing that these systems are quite diverse. At the same time, however, we

Table 7 Significant weights of criteria using various methods

		MCA-Saaty (%)	MCA-Fuller (%)	MCA-geometric mean line (%)	Saaty matrix (%)
D	Energy performance	26.45	32.69	22.5	27.99
D1	Operation energy	56.25	63.64	42.86	69.16
D1.1	Energy for heating	23.08	29.52	23.08	43.83
D1.2	Energy for domestic hot water	23.08	29.52	23.08	30.38
D1.3	Energy for mechanical ventilation and cooling	23.08	29.52	23.08	10.86
D1.4	Energy for lighting	17.59	10.48	17.95	7.46
D1.5	Energy for appliances	12.82	0.95	12.82	7.46
D2	Active systems using renewable energy sources	25	33.33	33.33	17.62
D2.1	Solar system and/or photovoltaic technology	36	63.64	36	53.5
D2.2	Technology for renewable energy other than solar energy	32	18.18	32	16.5
D2.3	Heat recuperation	32	18.18	32	22
D3	Energy management	18.75	3.03	23.81	13.23
D3.1	Energy management system	50	50	50	50
D3.2	Facility management	50	50	50	50

Table 8 Means of assessment of energy performance

D	Energy performance		26.45 %
D1	Operation energy		56.25 %
D1.1	Energy for heating		23.08 %
Intent	To determine energy needs for heating	Score	Weight
Indicator	Class of energy for heating according to energy performance of buildings directive (EPBD) and related standards.		
Negative	Energy for heating is in a class lower than C.		-1
Acceptable practice	Energy for heating is in class C.		0
Good practice	Energy for heating is in class B.		3
Best practice	Energy for heating is in class A.		5
D1.2	Energy for domestic hot water		23.08 %
Intent	To determine energy needs for domestic hot water.	Score	Weight
Indicator	Class of energy for domestic hot water according to standards for energy performance of buildings.		
Negative	Energy for domestic hot water is in a class lower than C.		-1
Acceptable practice	Energy for domestic hot water is in class C.		0
Good practice	Energy for domestic hot water is in class B.		3
Best practice	Energy for domestic hot water is in class A.		5
D1.3	Energy for mechanical ventilation and cooling		23.08 %
Intent	To determine energy needs for mechanical ventilation and cooling.	Score	Weight
Indicator	Class of energy for mechanical ventilation and cooling according to standards for energy performance of buildings.		
Negative	Energy for mechanical ventilation and cooling is in a class lower than C.		-1
Acceptable practice	Energy for mechanical ventilation and cooling is in class C.		0
Good practice	Energy for mechanical ventilation and cooling is in class B.		3
Best practice	Energy for mechanical ventilation and cooling is in class A.		5
D1.4	Energy for lighting		17.59 %
Intent	To determine energy needs for lighting.	Score	Weight
Indicator	Class of energy for lighting according to standards for energy performance of buildings.		
Negative	Energy for lighting is in a class lower than C.		-1
Acceptable practice	Energy for lighting is in class C.		0
Good practice	Energy for lighting is in class B.		3
Best practice	Energy for lighting is in class A.		5
D1.5	Energy for appliances		12.82 %
Intent	To minimise energy needs for appliances.	Score	Weight
Indicator	Using electric appliances with low consumption of electric energy, which is determined by energy class.		
Negative	At least one electric appliance is in energy class lower than A or B.		-1
Acceptable practice	Fewer than 2/3 of electrical appliances are in energy class A, the others are in B.		0
Good practice	At least 2/3 of electrical appliances are in energy class A and 1/3 is in B.		3
Best practice	All electrical appliances are in energy class A.		5
D2	Active systems using renewable energy sources		25 %
D2.1	Solar system and/or photovoltaic technology		36 %
Intent	To minimise energy consumption by using active solar components or photovoltaic technology.	Score	Weight
Indicator	Using solar energy for domestic hot water and heating or transformation to electric energy.		
Negative	Solar system and/or photovoltaic technology is not installed.		-1
Acceptable practice	Energy generated by solar system and/or photovoltaic technology covers <30 % of energy consumption.		0

Table 8 continued

Good practice	Energy generated by solar system and/or photovoltaic technology covers 30–60 % of energy consumption.		3
Best practice	Energy generated by solar system and/or photovoltaic technology covers >60 % of energy consumption.		5
D2.2	Technology for renewable energy other than solar energy		32 %
Intent	To minimise energy consumption by using technology for renewable energy sources other than solar energy.	Score	Weight
Indicator	Using renewable energy other than solar energy for domestic hot water and heating/cooling or transformation to electric energy.		
Negative	Technology for renewable energy is not installed.		-1
Acceptable practice	Renewable energy other than solar energy for domestic hot water and heating/cooling or transformation to electric energy covers <30 % of consumption energy.		0
Good practice	Renewable energy other than solar energy for domestic hot water and heating/cooling or transformation to electric energy covers 30–60 % of consumption energy.		3
Best practice	Renewable energy other than solar energy for domestic hot water and heating/cooling or transformation to electric energy covers >60 % of consumption energy.		5
D2.3	Heat recuperation		32 %
Intent	To utilise recovery heat.	Score	Weight
Indicator	Using a barrier-layer photocell.		
Negative	Heat recuperation is not utilised.		-1
Acceptable practice	Under 30 % of recovery heat is utilised for heat recuperation.		0
Good practice	30–60 % of recovery heat is utilised for heat recuperation.		3
Best practice	Above 60 % of recovery heat is utilised for heat recuperation.		5
D3	Energy management		18.75 %
D3.1	Energy management system		50 %
Intent	To improve the energy performance of a building.	Score	Weight
Indicator	Utilising an energy management system according to ISO 50001.		
Negative	No energy management system is established for the building.		-1
Acceptable practice	Requirements specified in standard for energy management system are 50 % met.		0
Good practice	Requirements specified in standard for energy management system are 75 % met.		3
Best practice	Requirements specified in standard for energy management system are 100 % met.		5
D3.2	Facility management		50 %
Intent	To improve performance of systems in the building.	Score	Weight
Indicator	Utilising facility management system according to EN 15221 series of standards.		
Negative	System of facility management is not established for the building.		-1
Acceptable practice	Requirements specified in standard for facility management are 50 % met.		0
Good practice	Requirements specified in standard for facility management are 75 % met.		3
Best practice	Requirements specified in standard for facility management are 100 % met.		5

can see that the approaches of assessment are essentially not that different. Several differences are found in the terminology, but different indicators in the systems are often evaluated under similar headings. Classification and certification of buildings differ from one country to another in accordance with national conditions and requirements. The sensitivity of methods and independence of indicators are progressively ensured with continuous modification and specification of methods and tools. It, therefore, follows that good building environmental assessment requires a multidisciplinary and multi-criteria approach.

The developed building environmental assessment system applicable in the conditions of Slovakia consists of 6 main fields and 52 indicators and incorporates systems and methods used in many other countries. The main fields are building site and project planning, building constructions, the indoor environment, energy performance, water management and waste management.

The main features of the system include the following:

- BEAS is a multi-criteria system and includes environmental, social and cultural aspects;
- the evaluated indicators respect European and Slovak standards, rules, studies and experiments;
- the system allows the establishment of indicator weights that reflect their varying importance in the region;
- designers can specify targets for building performance in terms of various aspects;
- assessors can accept the assessment made by designers.

Based on the comparison of the main fields in BEAS, it is possible to assert that the field of energy performance has the highest percentage weight significance (26.45 %). The percentage weights of others fields are 14.71 %—site selection and project planning, 20.59 %—building construction, 23.49 %—indoor environment, 8.88 %—water management and 5.88 %—waste management.

The theoretical level of existing knowledge about building environmental assessment has been thoroughly analysed and applied, making it necessary to implement this knowledge in construction practice. For the purpose of system verification, a statistically significant set of buildings needs to be evaluated, the outcome of which will be modification of the fields and indicators weighting. Our future research work will be an implementation of aspects and indicators given in European standards for the sustainability assessment of buildings to the BEAS applicable in Slovakia and a comparison of BEAS with significant and globally used building environmental assessment systems.

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Authors' contributions SV has participated in preparing the state of the art of energy performance of buildings, proposal of indicators of energy performance field. EKB used the MCDA for determination of significant weights and evaluating of indicators of energy performance field. Together with SV evaluated the results from MCDA and processed conclusion. All authors read and approved the final manuscript.

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